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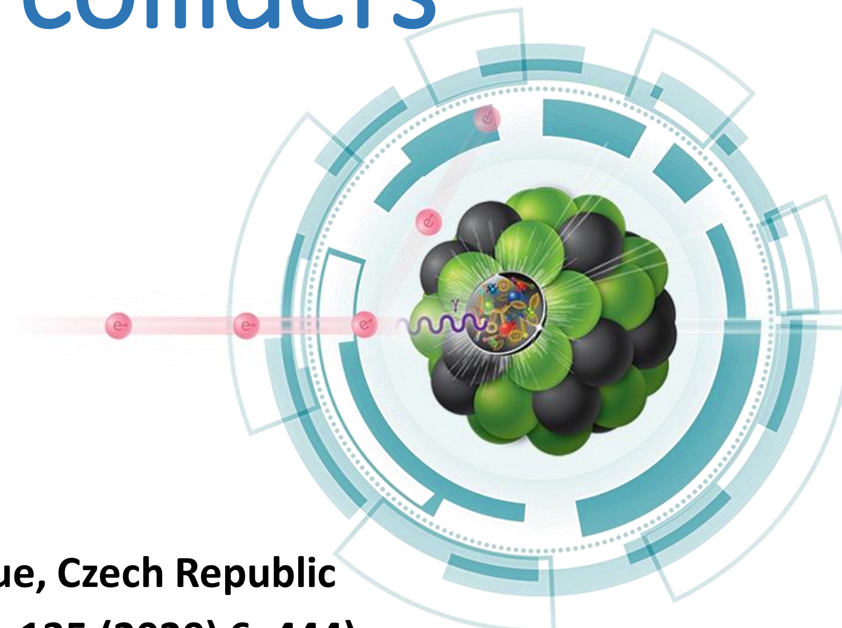
# Nuclear shadowing in DIS for future electron-ion colliders



*Michal Krelina*

In collaboration with

*Jan Nemchik*

**FNSPE, Czech Technical University in Prague, Czech Republic**

**Based on arXiv:2003.04156 (Eur.Phys.J.Plus 135 (2020) 6, 444)**

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# Outline

- **Nuclear shadowing** in terms of **color dipole formalism**
- Results for $F_2^A$
- Preliminary results for centralities
- Where else we can apply these results
- Conclusions

# Color Dipole Framework

- Reference frame: **rest frame** of the nucleus
- Virtual photon fluctuations:
  - Fock component expansion:
    $|\gamma^*\rangle \rightarrow |q\bar{q}\rangle + |q\bar{q}G\rangle + |q\bar{q}2G\rangle + |q\bar{q}3G\rangle + \cdots$
  - For DIS at proton target **only the first** Fock component
- Cross section:

$$\sigma_{tot}^{\gamma^* N}(x_{Bj}, Q^2) = \int d^2r \int_0^1 d\alpha \left|\Psi_{q\bar{q}}^{T,L}(\vec{r}, \alpha, Q^2)\right|^2 \sigma_{q\bar{q}}(\vec{r}, s)$$

See more: arXiv:2003.04156

  - $\gamma^* \rightarrow q\bar{q}$ wave function:

$$\Psi_{q\bar{q}}^{T,L}(\vec{r}, \alpha, Q^2) = \frac{\sqrt{N_c \alpha_{em}}}{2\pi} Z_q \, \bar{\chi} \hat{O}^{T,L} \chi K_0(\epsilon r)$$

  - *Improvement:* non-perturbative interaction $q - \bar{q}$

See more: Phys. Rev. D62, 054022 (2000)

# Nuclear shadowing

- **Nuclear shadowing:** shadowing of hadronic components of virtual photon caused by their multiple scattering inside the target
- Coherence length (CL)/time:
  - Controls the dynamics of nuclear shadowing
  - Photon fluctuation **lifetime**
  - For example: lowest Fock component $|q\bar{q}\rangle$

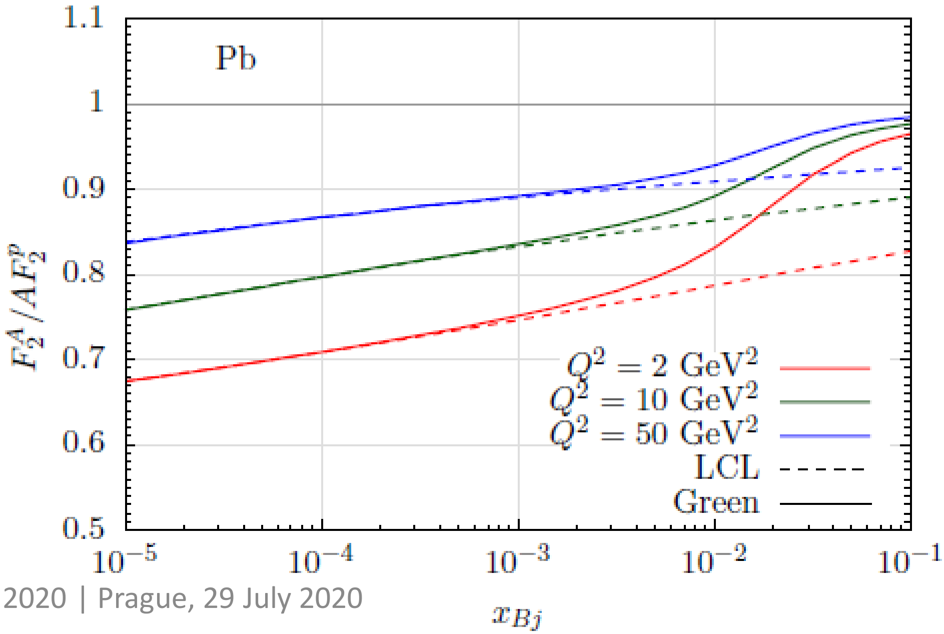
$$l_c = \frac{2\nu}{Q^2 + M_{q\bar{q}}^2}, \quad \nu = \frac{Q^2}{2m_N x_{Bj}}$$

  - CL is related to the longitudinal momentum $q_c = 1/l_c$

# Nuclear shadowing limits

- **Eikonal approximation** (LCL – long coherence length)
  - $\sigma_{q\bar{q}} \to 2\left(1 - e^{-\frac{1}{2}T_A(b)\sigma_{q\bar{q}}}\right)$
  - This is valid for $\boldsymbol{l_c} \gg \boldsymbol{R_A}$
  - I.E.: for small $x_{Bj}$
- For all other $\boldsymbol{l_c}$ use the Green function technique
- Green technique is more important with Fock components, because

$$M^2_{q\bar{q}} \ll M^2_{q\bar{q}G} \ll M^2_{q\bar{q}2G} \ll \cdots$$



# Green Function Formalism

- For equations, see arXiv:2003.04156
- In high energy limit, the Green function takes a eikonalized form

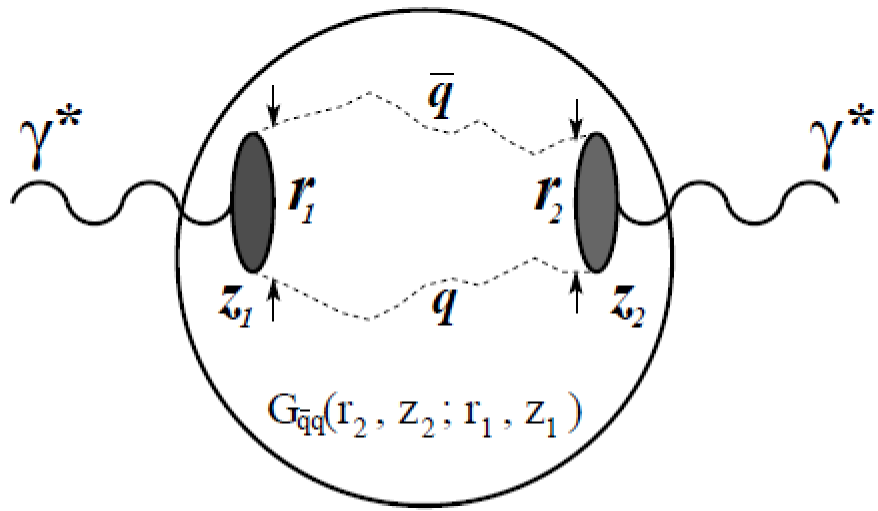



FIG. 1: A cartoon [5, 6, 10] for the first shadowing term $\Delta\sigma_{tot}(x_{Bj}, Q^2) = \Delta\sigma_{tot}(q\bar{q})$ in Eq. (2.1). The Green function $G_{q\bar{q}}(\vec{r_2}, z_2; \vec{r_1}, z_1)$ describes the propagation of the $q\bar{q}$ pair through the nucleus, which results from the summation over different paths of the $q\bar{q}$ pair.

# Quark vs gluon shadowing

- **Quark shadowing:** from $|q\bar{q}\rangle$ Fock component
- **Gluon shadowing:** from $|\boldsymbol{q\bar{q}G}\rangle + |q\bar{q}2G\rangle + |q\bar{q}3G\rangle + \cdots$ Fock components

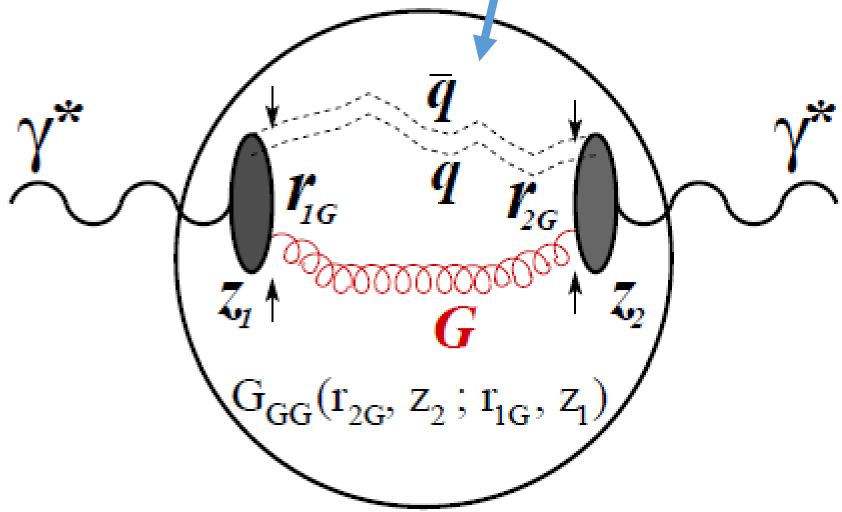



FIG. 3: A cartoon [52] for the shadowing term $\Delta\sigma_{tot}(x_{Bj}, Q^2) = \Delta\sigma_{tot}(q\bar{q}G)$. The Green function $G_{GG}(\vec{r}_{2G}, z_2; \vec{r}_{1G}, z_1)$ describes the propagation of the $q\bar{q}G$ system through the nucleus as a propagation of the effective gluon-gluon (color octet-octet) dipole neglecting the small transverse size of the color-octet $G \equiv q\bar{q}$ fluctuation.

# Gluon shadowing

- $\boldsymbol{\gamma^* \to q\bar{q}G}$ wave function
  - $\gamma^* \to GG$ approximation, valid for higher $Q^2$
  - The full $\gamma^* \to q\bar{q}G$ wave function in progress
- Small $\sigma_{q\bar{q}}(\vec{r}, s)$ approximation, i.e., $\sigma_{q\bar{q}} \sim C r^2$
  - Various ways to get factor $C$
  - We discuss two of them denotes as $C_0$ and more realistic $C_{\mathrm{eff}}$
- **Green function considered only** because
  - $M^2_{q\bar{q}G} = \frac{p_T^2}{\alpha_G(1-\alpha_G)} + \frac{M^2_{q\bar{q}}}{1-\alpha_G} \gg M^2_{q\bar{q}}$

See more: Phys. Rev. C62, 035204 (2000)

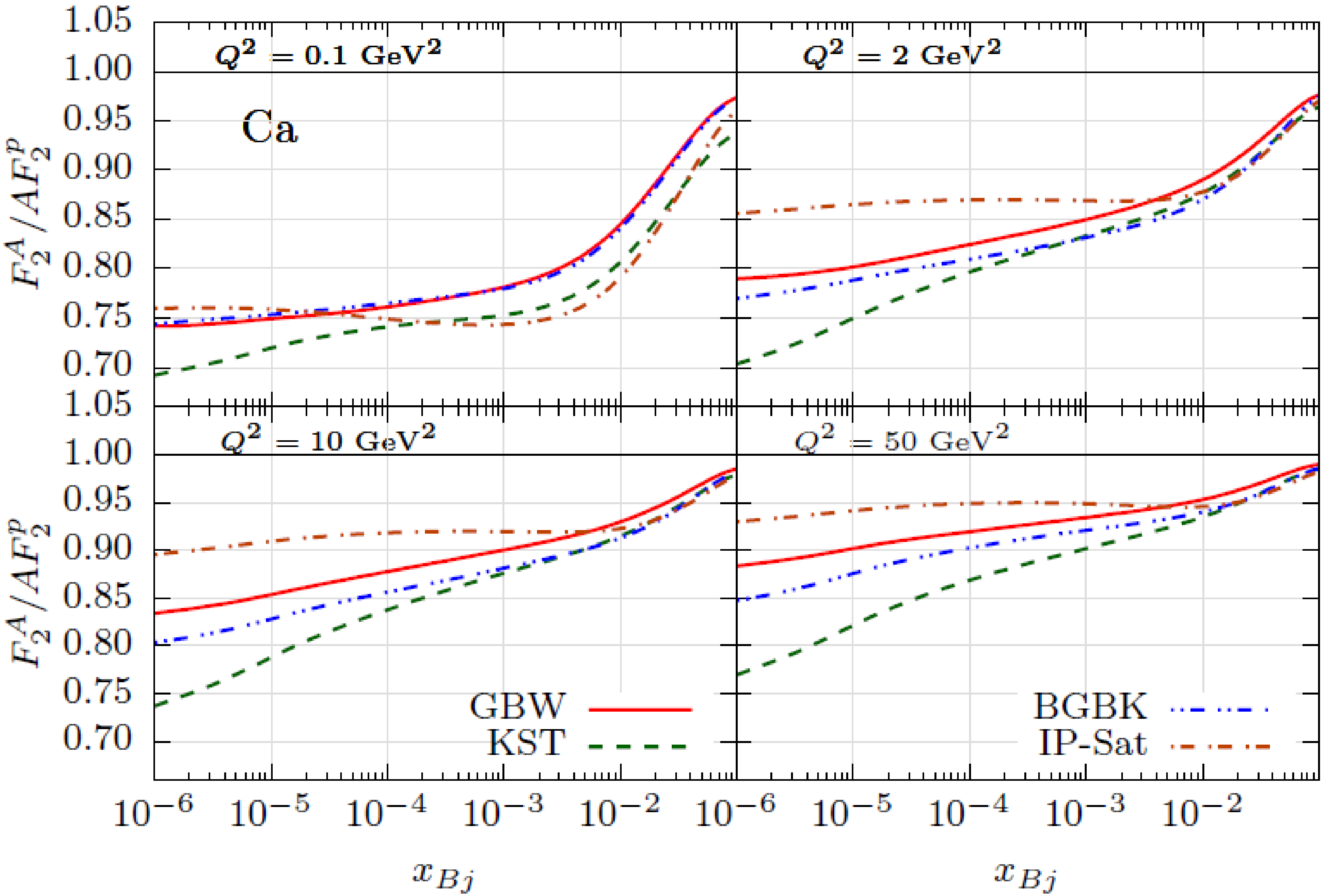
- Implemented as $\sigma_{q\bar{q}}(\vec{r}, s) \to R_G\left(b, x_{Bj}, Q^2\right)\sigma_{q\bar{q}}(\vec{r}, s)$

See more: Nucl. Phys. A696, 669 (2001)

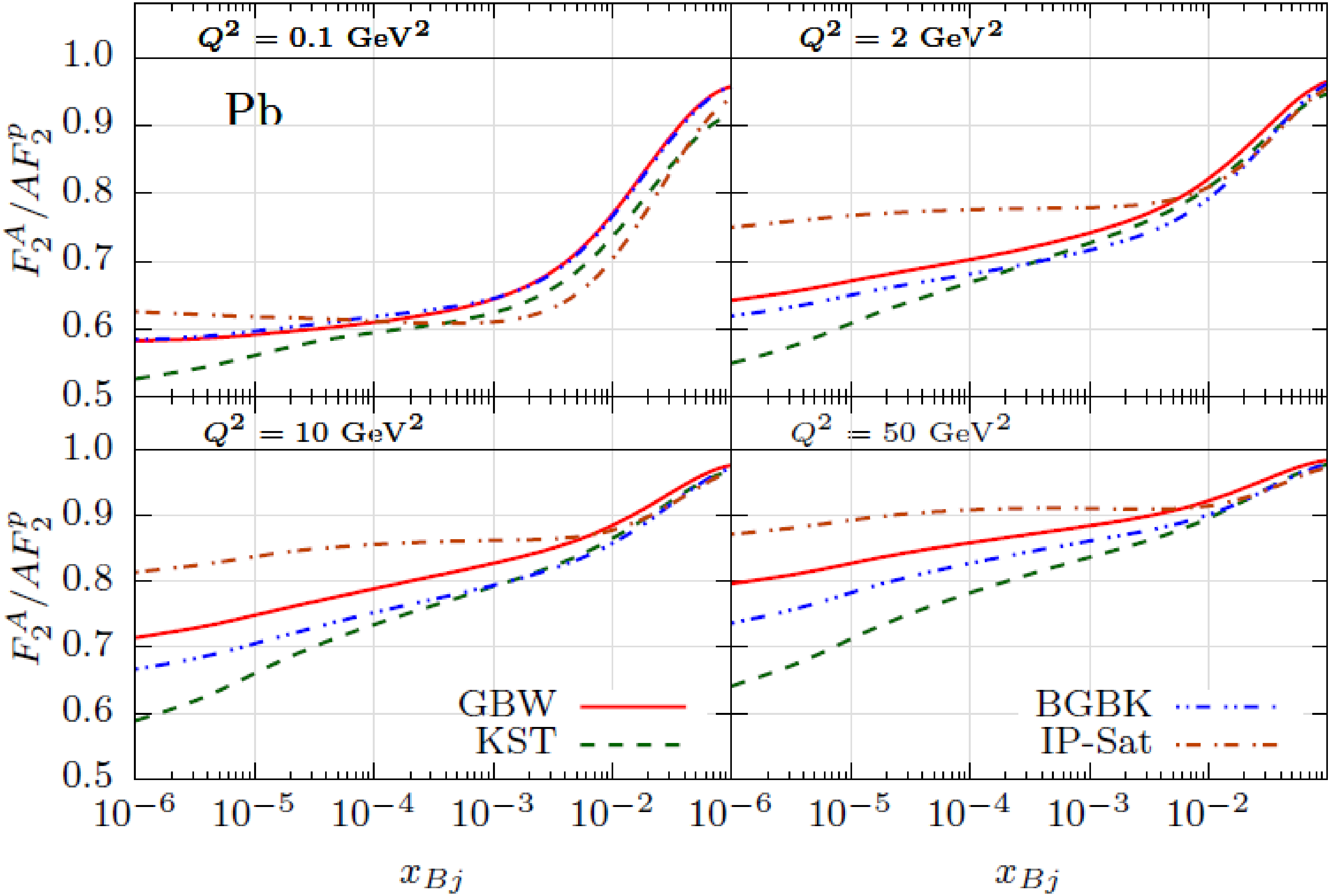
# BK equation (for nuclear target) note

- Balitsky-Kovchegov (BK) evolution equation
  - Summation of all Fock components with gluons is inherent, $l_c^{q\bar{q}}, l_c^{q\bar{q}G}, \dots, l_c^{q\bar{q}nG} \gg R_A$
  - Usually, people use the eikonalized form, where CL is longer than nucleus
  - Leading to **overestimated nuclear shadowing**
  - Therefore predictions for nuclear shadowing are not reliable at kinematics covered by EIC
  - Works better for perturbative region, large virtualities

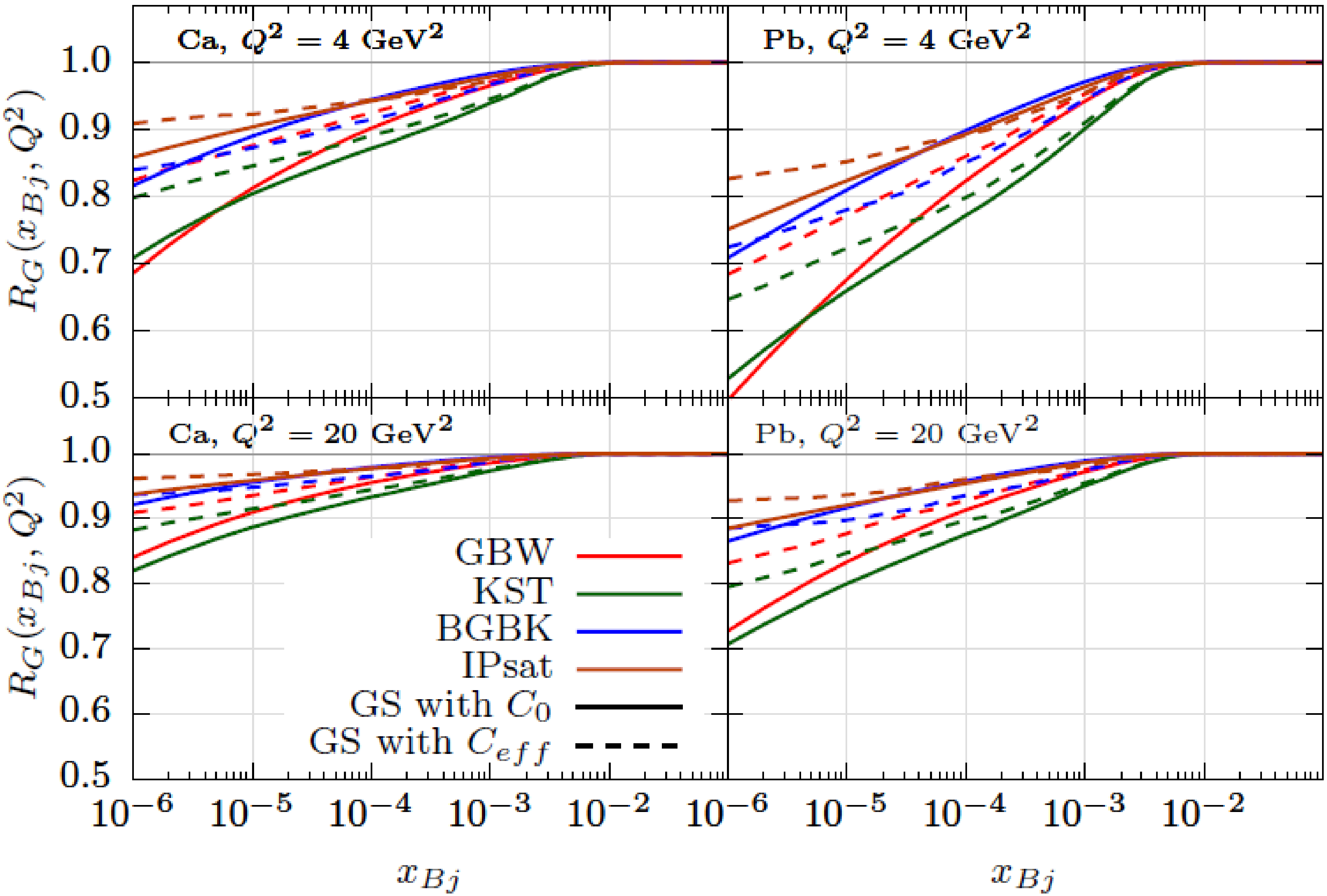
# Results: quark shadowing only



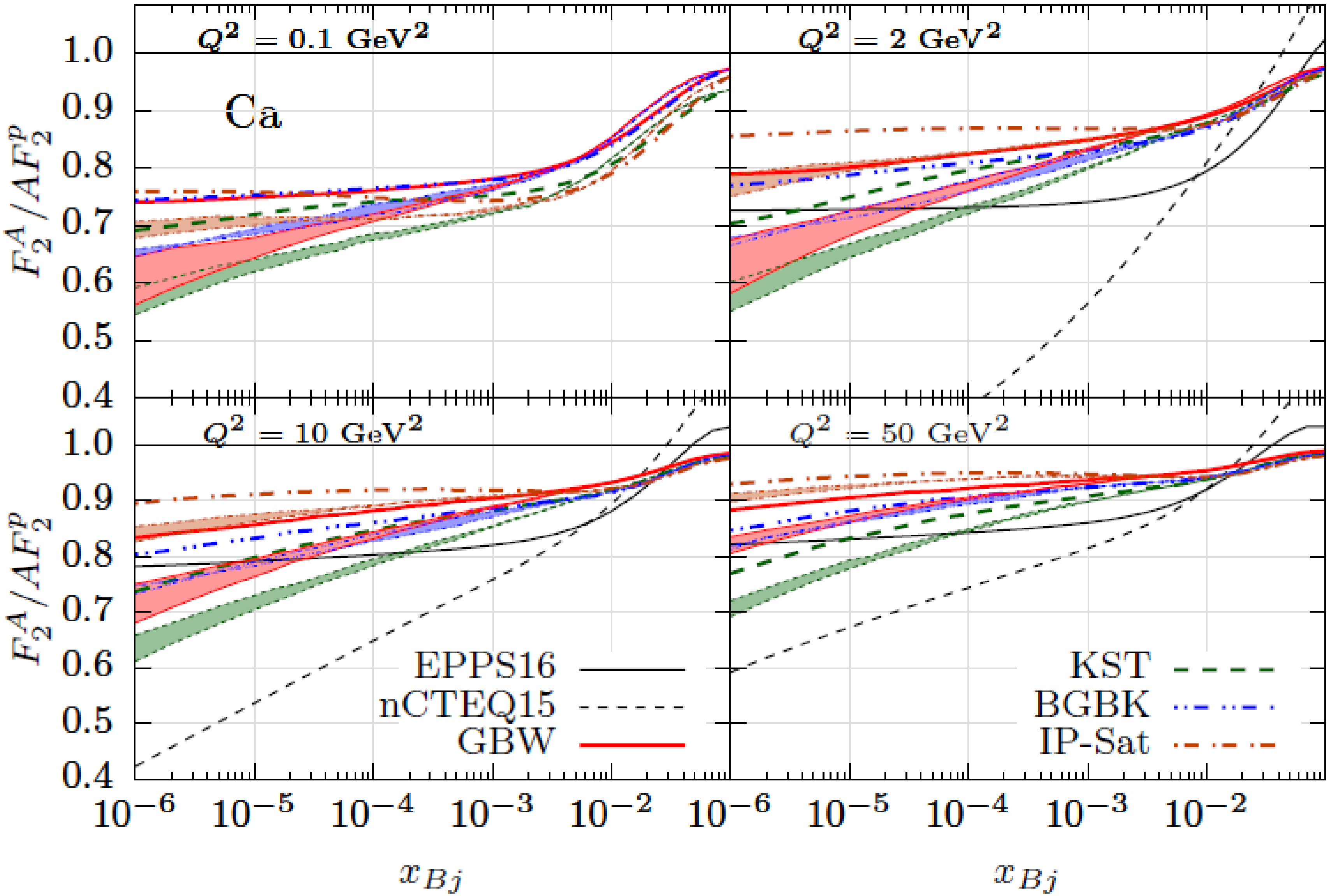
# Results: quark shadowing only



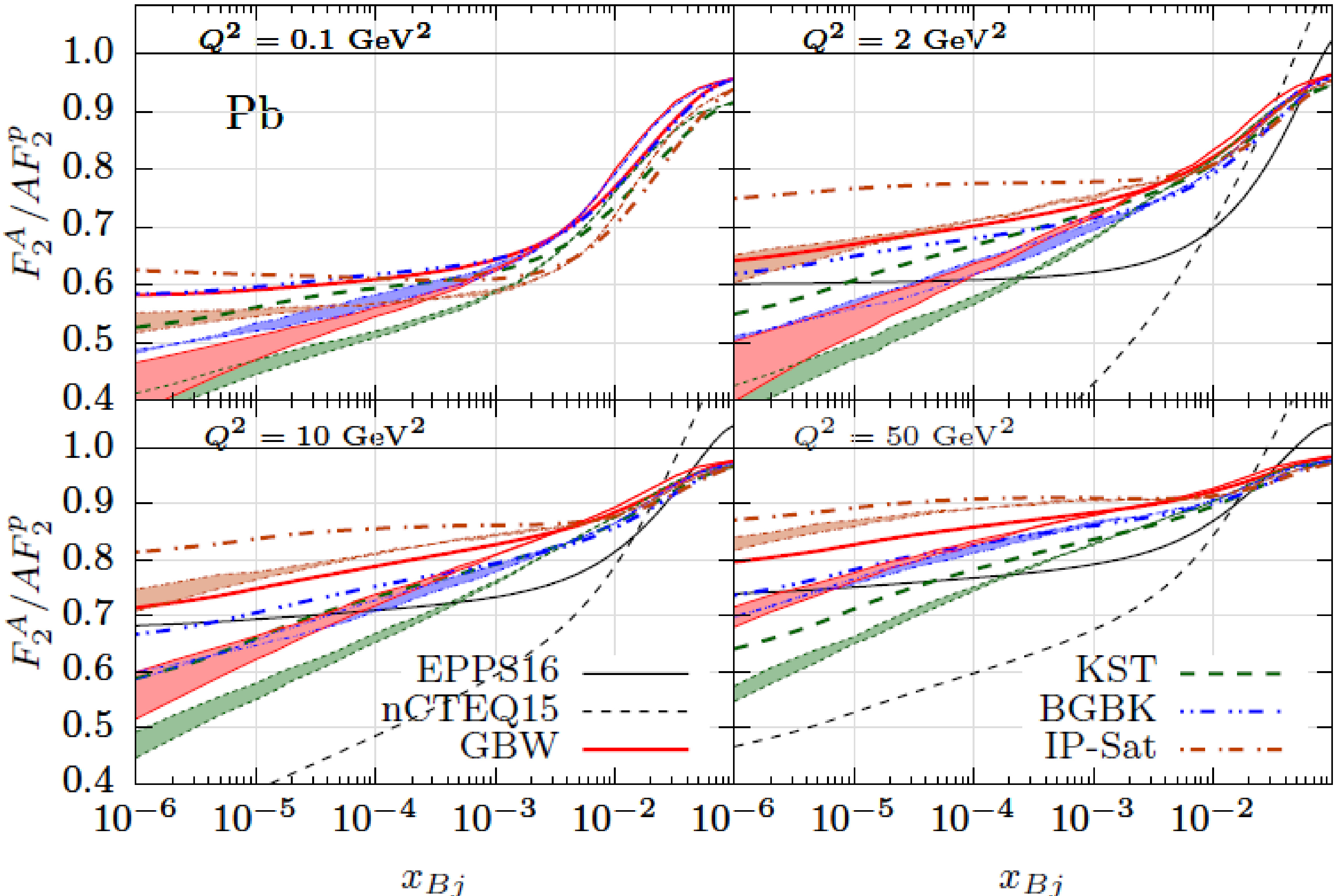
# Results: Gluon shadowing standalone



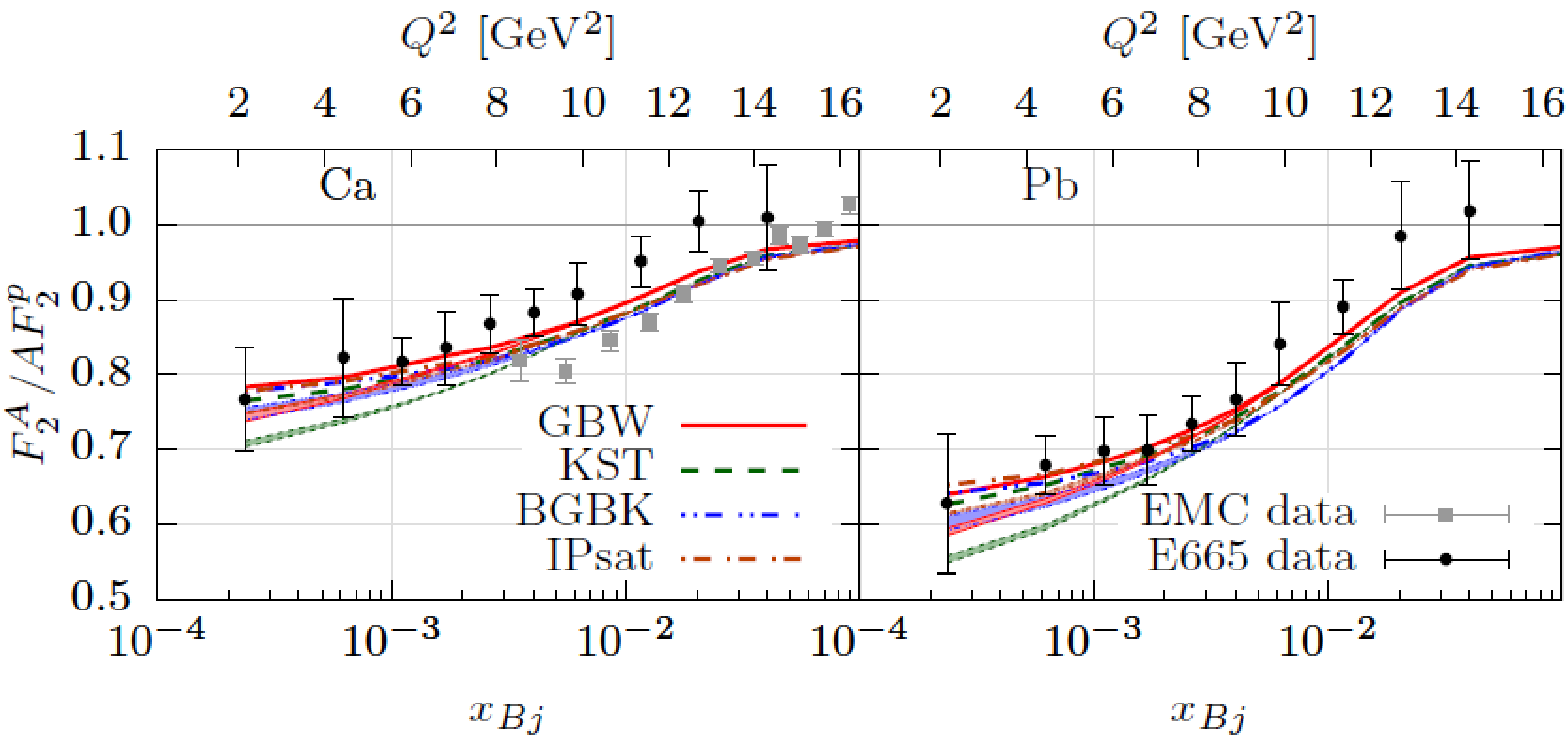
# Results: Full shadowing



# Results: Full shadowing



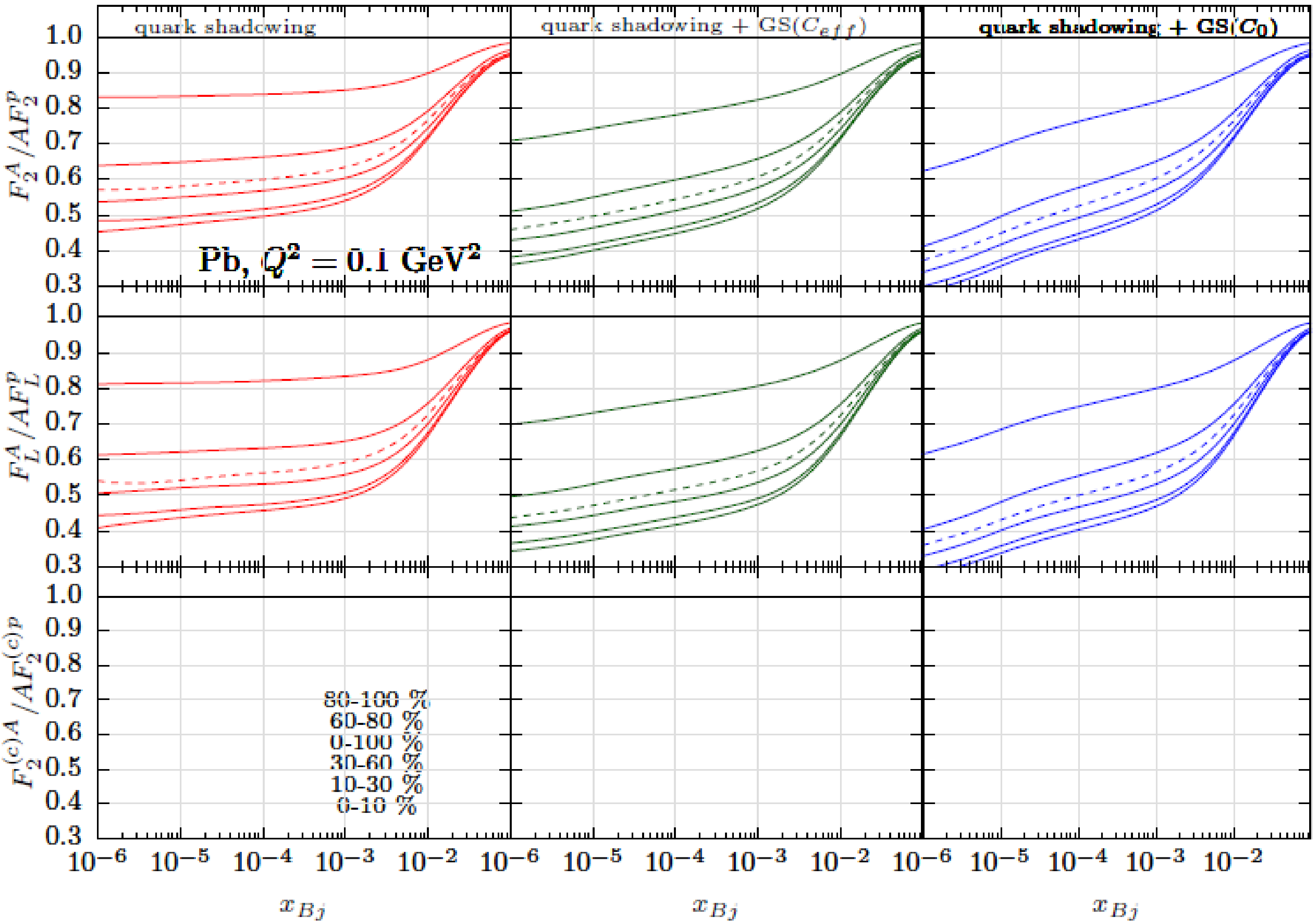
# Results: Data comparison



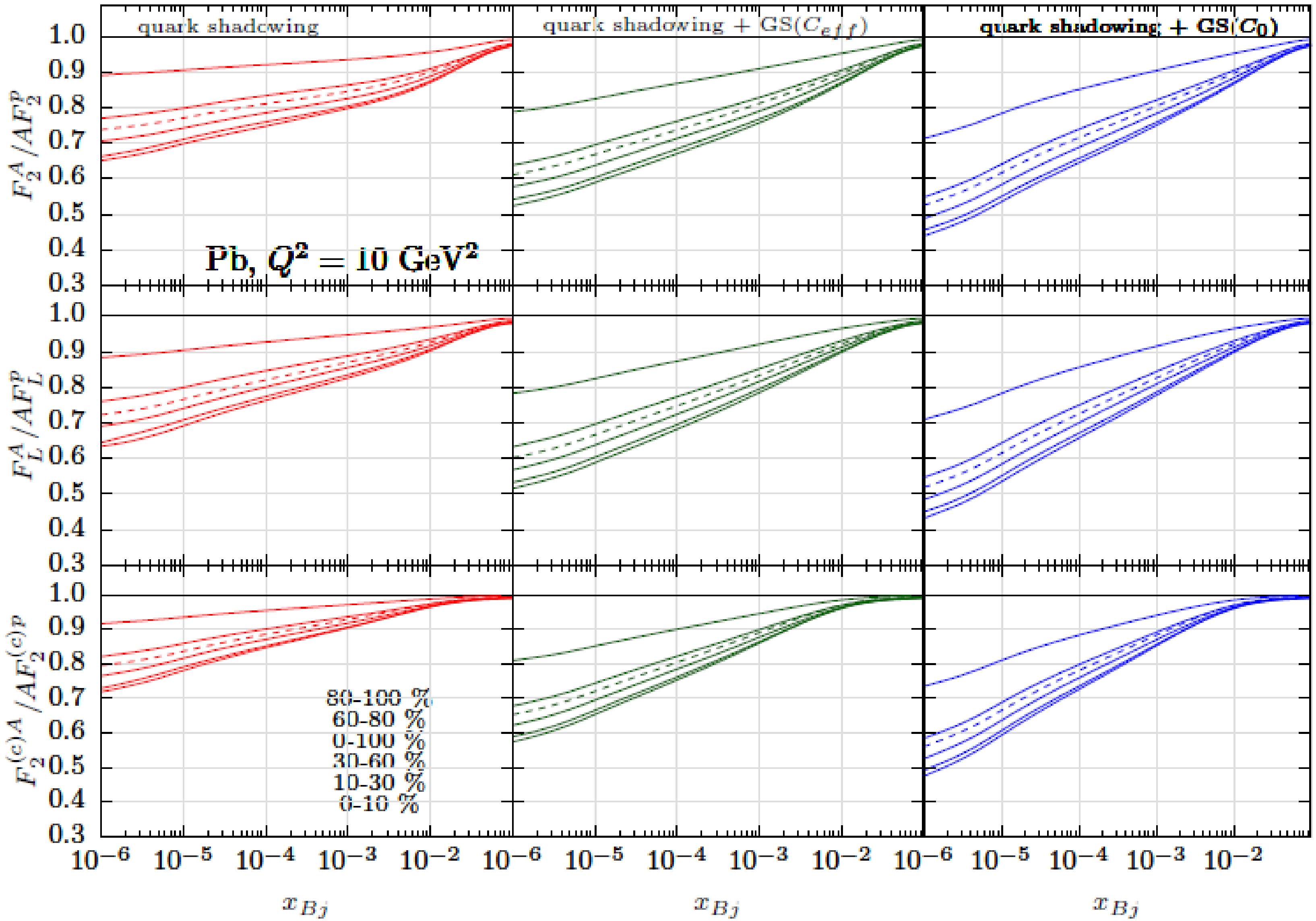
# Dipole Formalism allows more

- So far, we studied $F_2^A$ only
- **We can study more**:
  - Centrality dependence
  - $F_L^A, \sigma_L^A/\sigma_T^A$
  - $F_2^{c,A}, F_L^{c,A}, \sigma_L^{c,A}/\sigma_T^{c,A}$
  - $F_2^{b,A}, F_L^{b,A}, \sigma_L^{b,A}/\sigma_T^{b,A}$

# Results: Centrality



# Results: Centrality

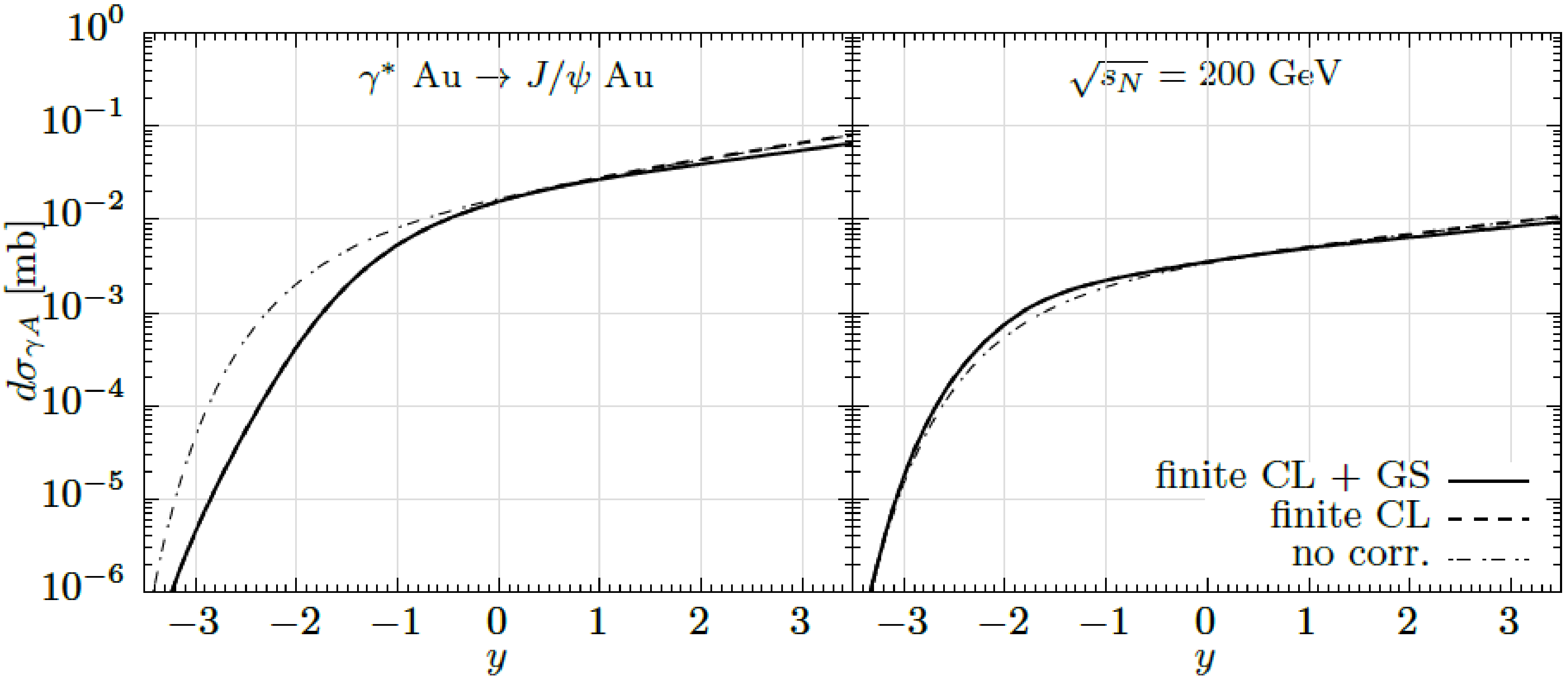


# Coherence correction applications

- **About coherence length we should care for all processes on nuclear target**
  - At least at lower $\sqrt{s_{NN}}$ energies (~RHIC, EIC), or
  - At LHC energies and large rapidities

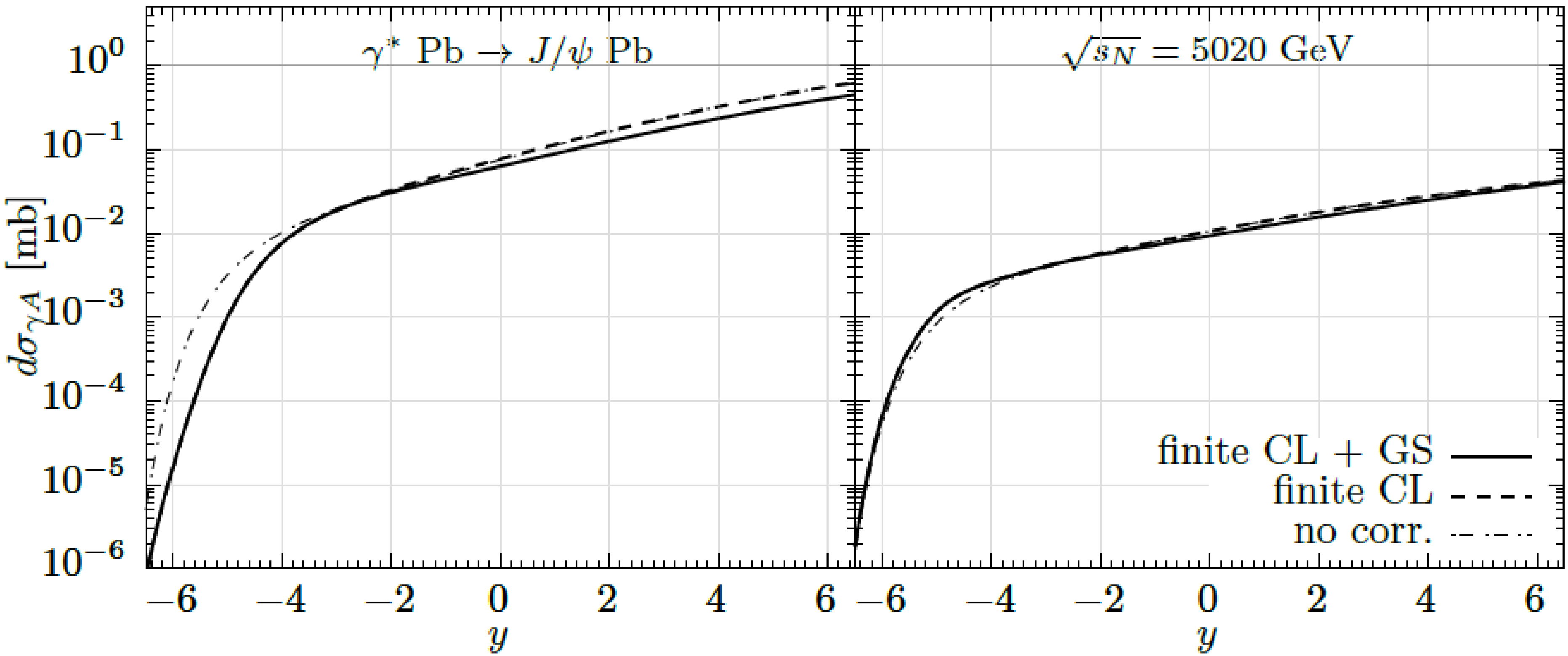
- *Example:*
  - Currently, the correct finite coherence length is **hot topic** for EIC that will probe energies, where the eikonal form is **not more safe**
    - VM photo/electro production, DVCS, di-jets, …
  - Other **hot topic** are UPC, see next slides…

# Application for VM photoproduction




PRELIMINARY (RHIC energy)

# Application for VM photoproduction




PRELIMINARY (LHC energy)

# Conclusions and outlooks

- **Improvements**
  - Non-perturbative effects in $q-\bar{q}$ interaction
  - Exact treatment of coherence length
  - Green function technique
- **Gluon shadowing**
  - Green function formalism important
  - Studied uncertainties of applied approximations
- **Main source of uncertainty:** dipole cross section $\sigma_{q\bar{q}}(\vec{r},s)$
  - $\sigma_{q\bar{q}}(\vec{r},s)$ is fitted from DIS
  - Nuclear DIS can help to exclude some of them
- **Color dipole formalism** offers **nature** calculations for nuclear targets

# Thank you for your attention!

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